Opening of the North Atlantic and Norwegian - Greenland Sea Basin - Lessons from the South Atlantic*

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Abstract

The Atlantic Mid Ocean Ridge can be traced from the Bouvet triple junction at latitude 54 degrees south, some 10,000 kilometers northwards via Iceland into the Norwegian Sea before joining with the Gakkel Ridge in the Arctic Ocean, via the Fram Strait.

Along the length of the divergent boundary of the Atlantic Mid-Ocean Ridge, the spreading center is offset by regularly spaced transform boundaries. These can be traced shoreward as deep-seated continental fracture zones beneath the sediment cover.

Lister et al. (1986) described upper plate and lower plate passive margins, separated by a detachment fault, which give rise to asymmetric conjugate margins after final continental breakup. The upper plate is characterized by a narrow continental shelf, with relatively little sedimentary accommodation space. It is relatively unstructured and has experienced uplift related to underplating. While on the opposite side of the mid ocean ridge, the conjugate lower plate is characterized by a wide continental shelf, which has abundant sedimentary accommodation space. It is complexly structured and exhibits bowed up detachment faults. Transfer faults offset marginal features and can cause the upper/lower plate polarity to change along the strike of the margin.

The Fram Strait is a transform margin which was initiated in the Eocene as a result of the onset of spreading in the North Atlantic. The sliding of the North American Plate past the Eurasian Plate during the opening of the North Atlantic created an upthrust zone that formed due to space constraints associated with low-angle convergent strike slip or transform motion. The easiest direction for space relief for the squeezed sediments is vertical, and a zone of downward tapering wedges and upthrust margins is created.

The Atlantic Mid Ocean Ridge transform boundaries can be traced across the oceanic crust towards the coast line, forming basement structural highs. These are related to volcanic activity along strike of these “leaky” fracture zones in the oceanic crust. These structures set up the initial structural framework of the continental margin basins. Syn-rift and post-rift deepwater sedimentation onlap these basement highs and the influence of the transfer zones continues to propagate into younger strata by differential compaction. These differential compaction

faults both act as a hydrocarbon migration pathway from deep-seated source rocks to shallower reservoirs, as well as influencing deepwater sediment delivery systems.

These zones of long-lived crustal weakness can be subsequently reactivated during later tectonic episodes, giving rise to inversion structures and complex compressive and transpressive/transtensional features. In offshore Equatorial Guinea, reactivation of the Ascension Fracture Zone during Senonian times created a series of transpressional anticlines, one of which contains the Ceiba Field.

Using the South Atlantic as an analogue, the integration of gravity, magnetic, and seismic data has been used to construct a simple symmetrical spreading model for the opening of the Norwegian Sea between Iceland and the island of Jan Mayen.

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OPENING OF THE NORTH ATLANTIC & NORWEGIAN – GREENLAND SEA BASIN – LESSONS FROM THE SOUTH ATLANTIC

Chris Parry

Presentation Outline

Norwegian – Greenland Sea Asymmetric Conjugate Margins:

- Upper Plate, Lower Plate,
- Svalbard Upthrust Zone.

South Atlantic:

- Non-Rigid Plates (Intra-Plate Deformations),
- Fracture Zones,
- Ceiba Field.

North Atlantic and Norwegian – Greenland Sea FZ Offshore/Onshore linkage:

- Onshore outcrop examples:
  - UK and South East Greenland,
- Seismic examples:
  - Jan Mayen Fracture Zones, Mid-Norway and North East Greenland.

Key message:

Mid-Ocean Ridge Fracture Zones Offshore/Onshore linked shear zones control:

- Coarse clastic sediment entry points,
- Provide hydrocarbon migration routes,
- Create trapping geometries,
- &
- Allow development of new models for exploration.

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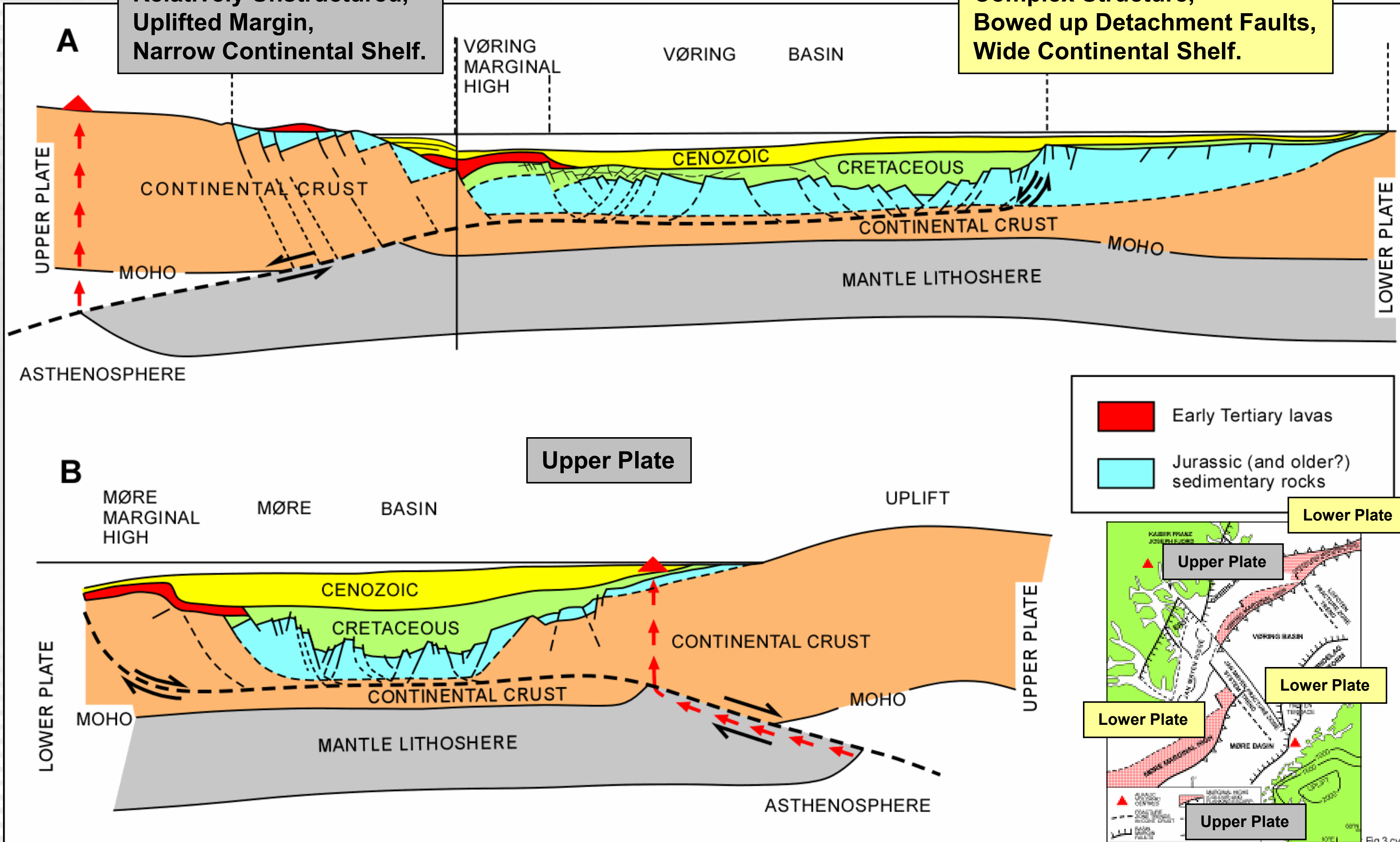
North Atlantic Asymmetric Conjugate Margins (1991)

Upper Plate:
Relatively Unstructured,
Uplifted Margin,
Narrow Continental Shelf.

Lower Plate:
Complex Structure,
Bowed up Detachment Faults,
Wide Continental Shelf.



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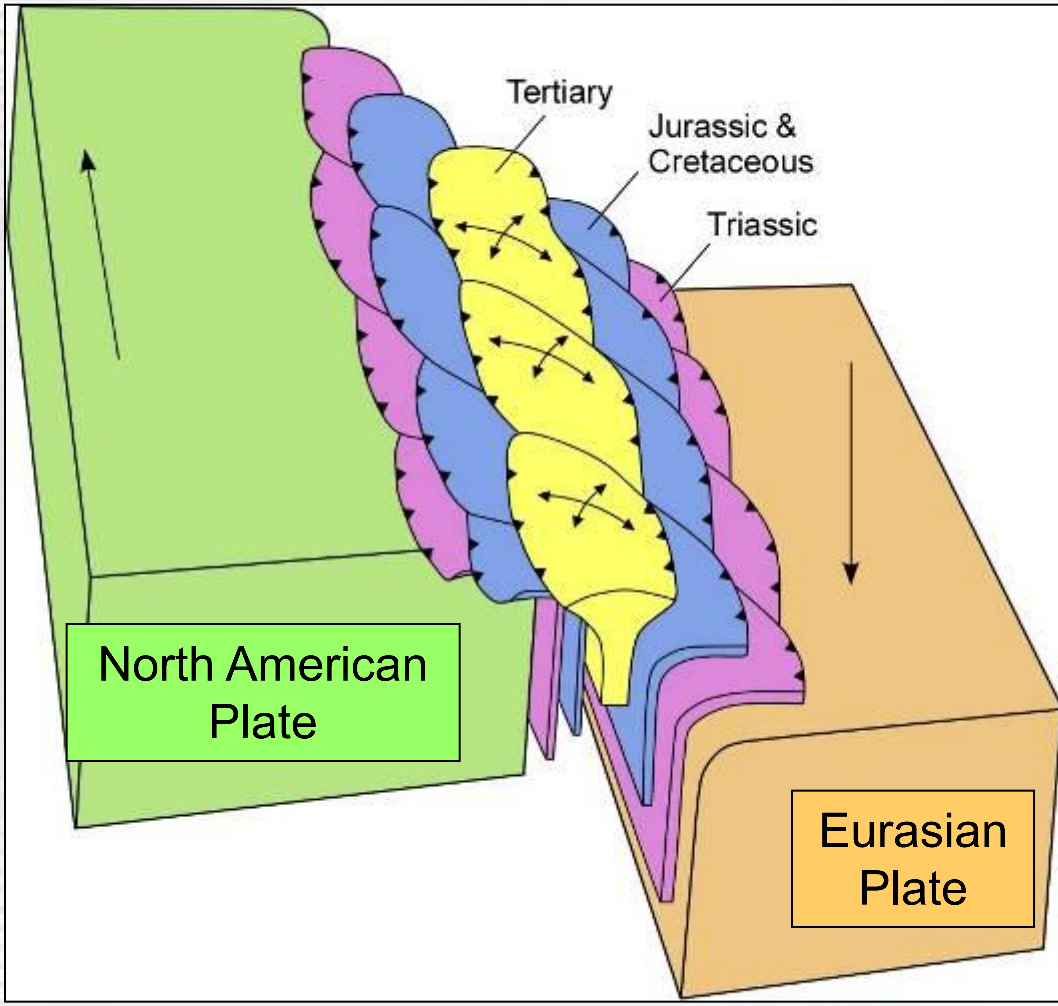
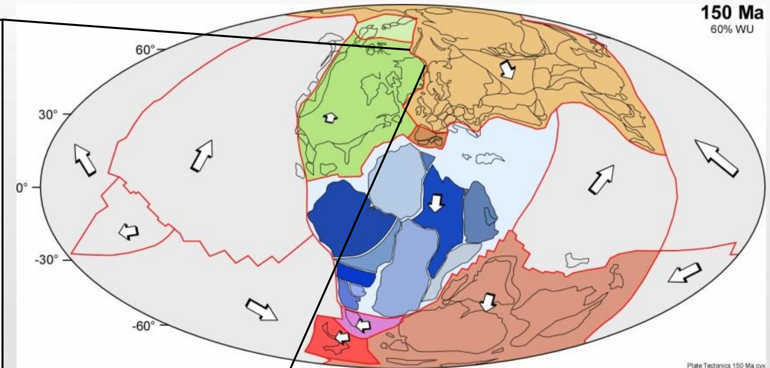
Convergent Strike Slip or Transform Motion Upthrust Zone

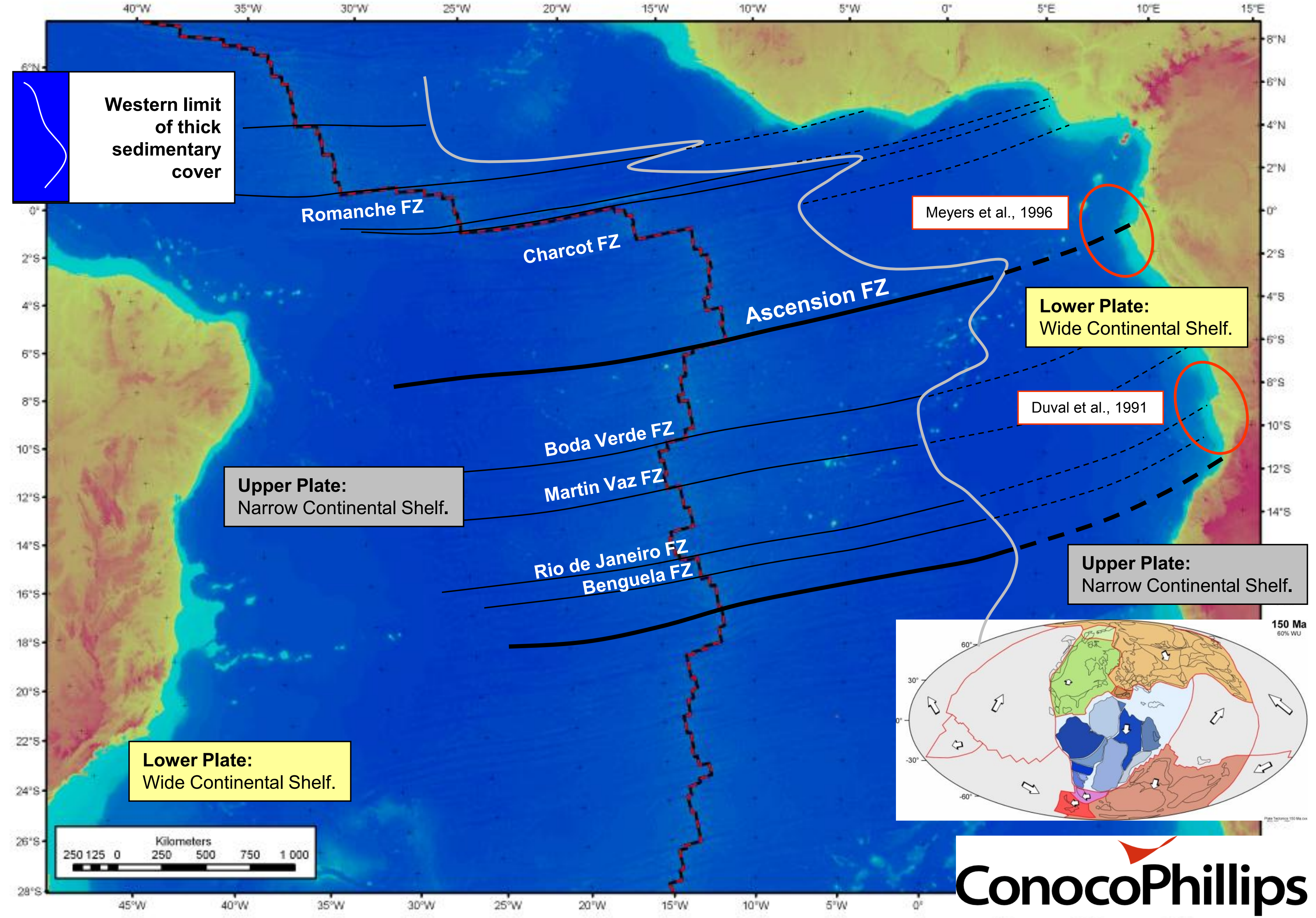




- Two plates moving at low convergent angle causes space problem.
- Easiest direction for relief is upwards.
- Upthrusts are not necessarily symmetrical.
- Faults coalesce and anastomose with depth.

Modified after Lowell, J.D.,1972 Spitzbergen Tertiary Orogenic Belt and Fracture Zone. Geol. Soc. Am. Bull., pp. 3091-3102

Fracture Zones of the South Atlantic



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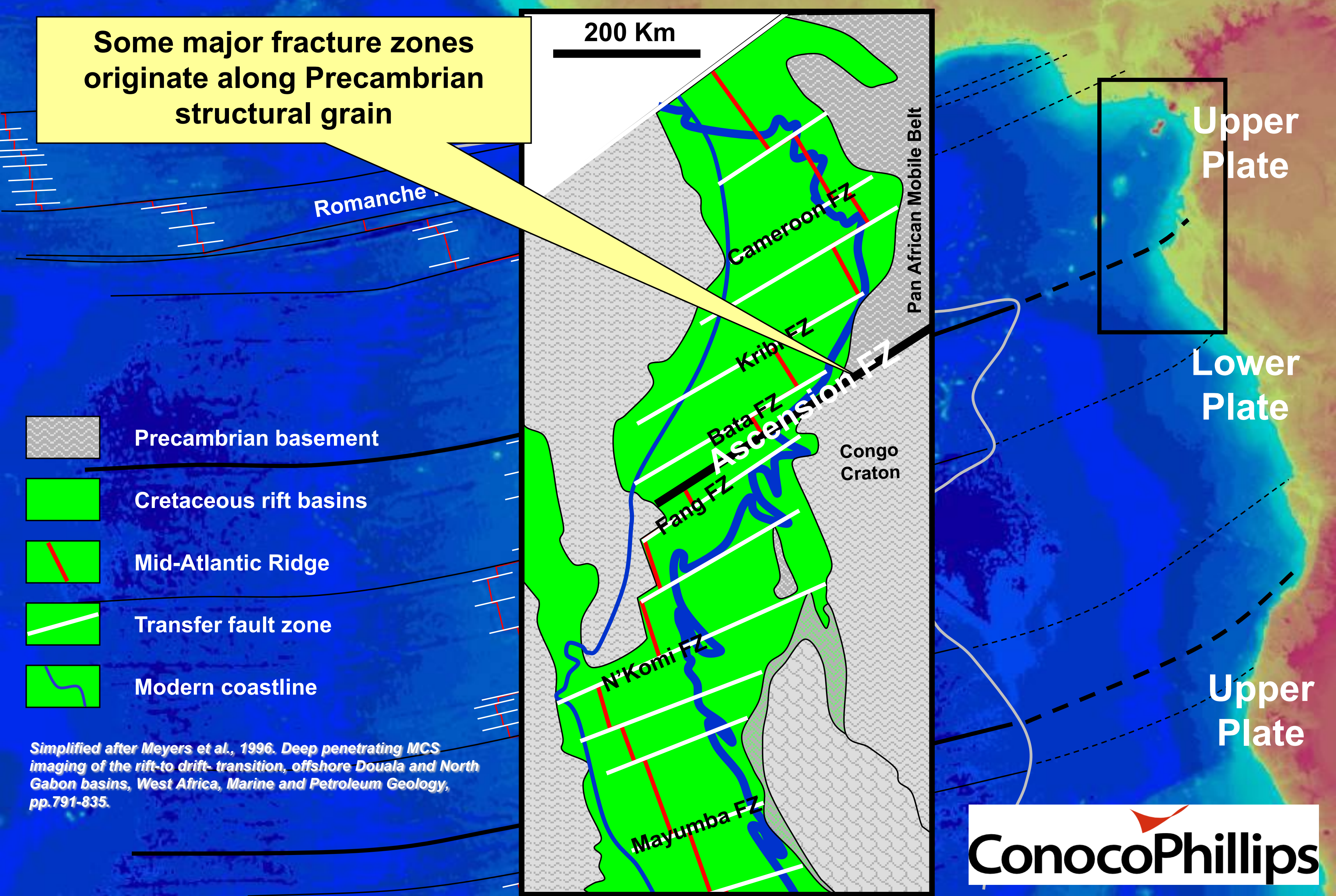
Rio Muni & Gabon Basins: Cretaceous Pre-Rift Configuration



Simplified after Meyers et al., 1996. Deep penetrating MCS imaging of the rift-to drift- transition, offshore Douala and North Gabon basins, West Africa, Marine and Petroleum Geology, pp.791-835.

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Equatorial Guinea Ceiba Field, Senonian inversion structure related to reactivation of Ascension Fracture Zone

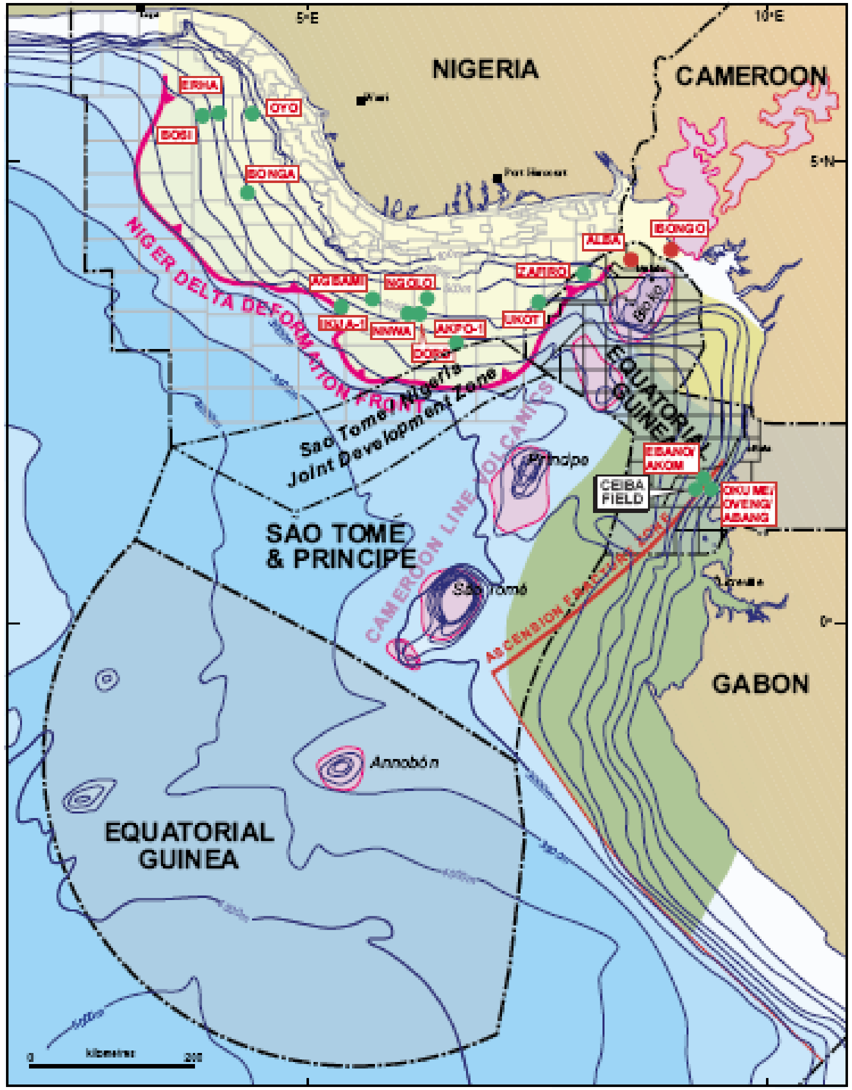


Figure 1 - Regional map of Equatorial Guinea and neighboring countries, showing the location of the Ceiba Field (Equatorial Oil, 2002).

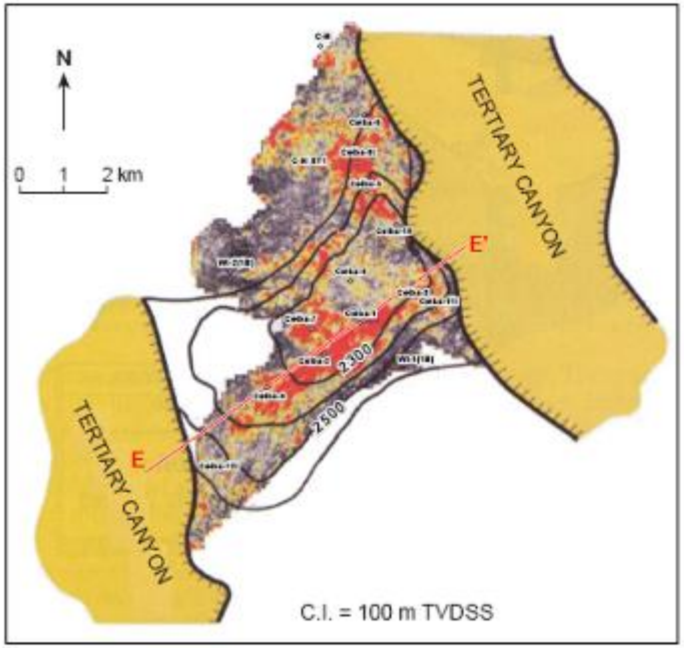


Figure 12 - Structure of the top of the reservoir in the Ceiba Field, superimposed on a seismic amplitude map. Also shown are the mud-filled Tertiary canyons on the SW and NE margins of the field that have eroded through the Coniacian reservoir interval (Dailly et al., 2002). The location of seismic section E-E' (Fig. 13) is shown.

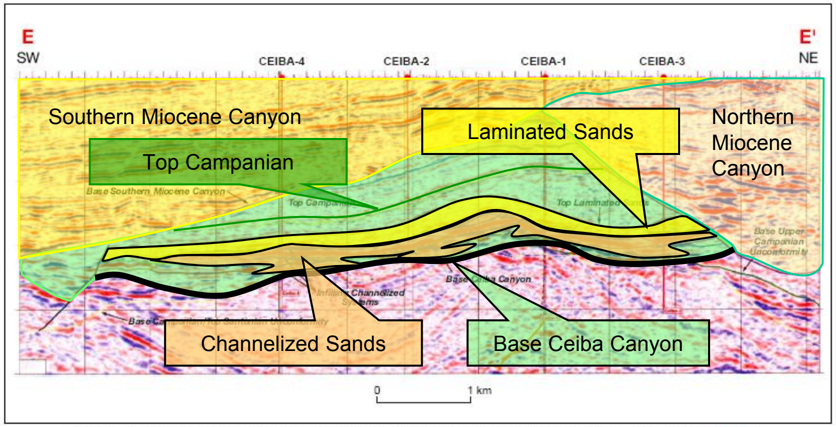
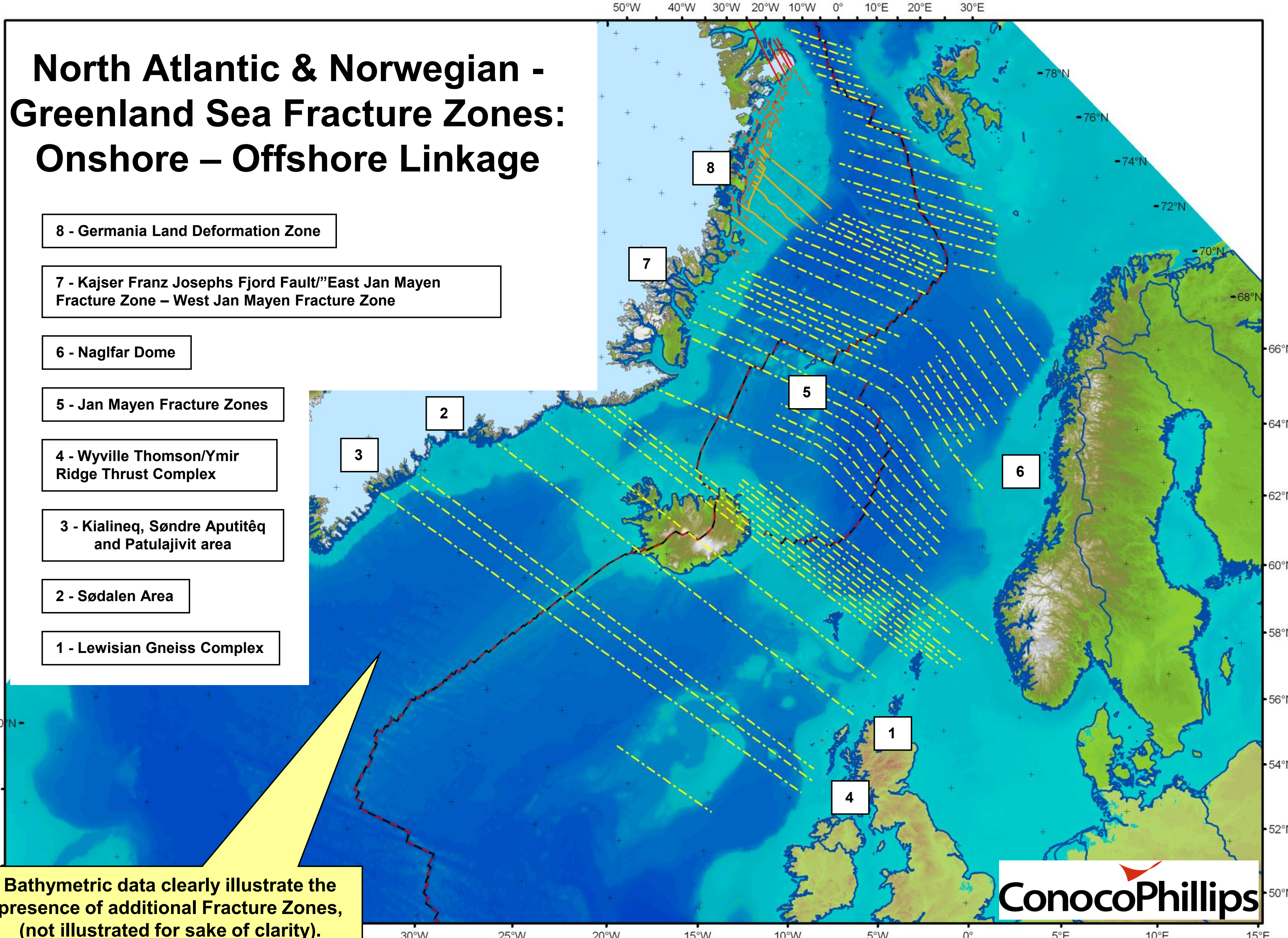


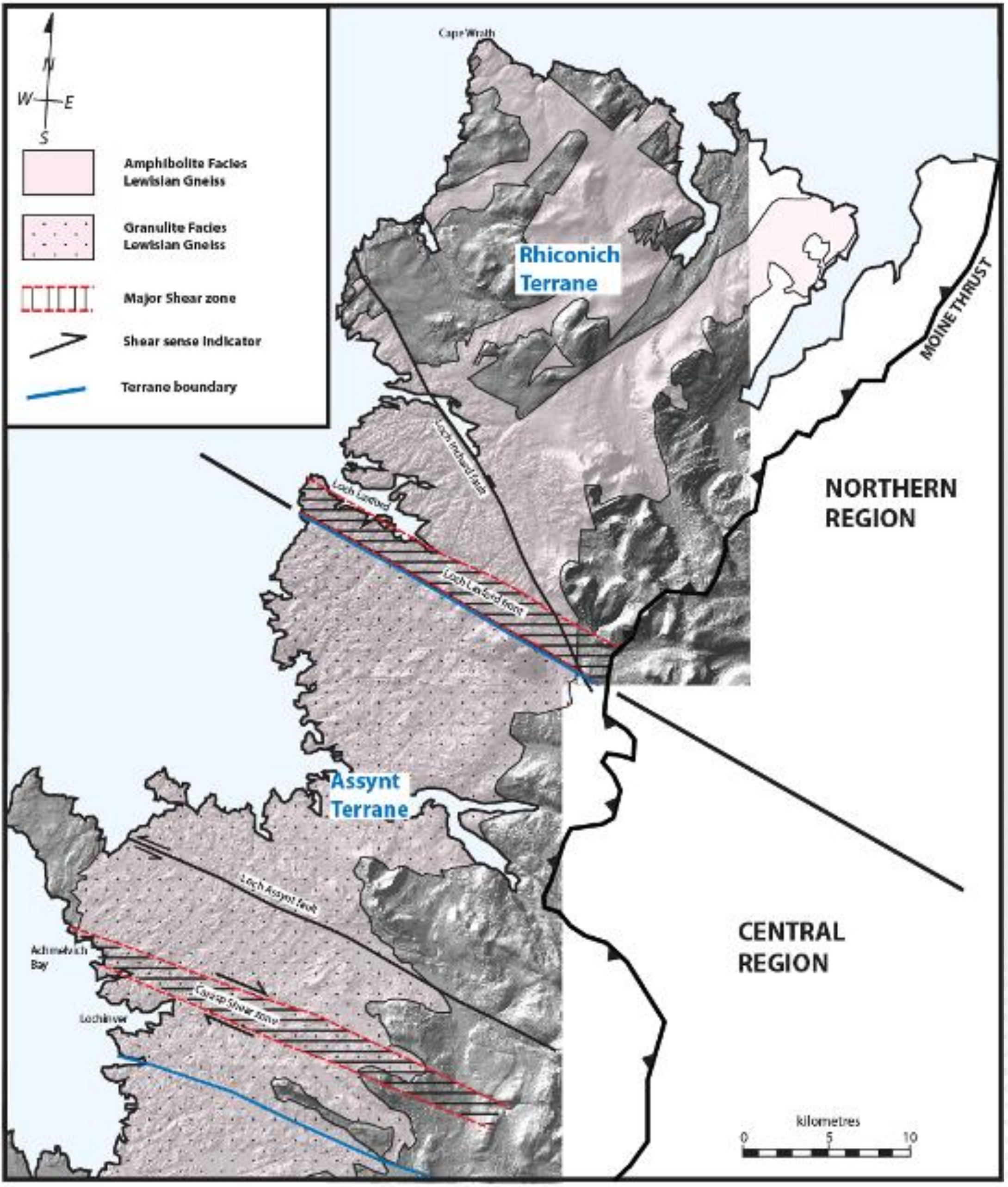
Figure 13 - SW-NE seismic section E-E' through the Ceiba Field (Dailly et al., 2002). The location of the section is shown in Figure 12.

North Atlantic & Norwegian - Greenland Sea Fracture Zones: Onshore – Offshore Linkage

- 8 - Germania Land Deformation Zone
- 7 - Kajser Franz Josephs Fjord Fault/"East Jan Mayen Fracture Zone – West Jan Mayen Fracture Zone
- 6 - Naglfar Dome
- 5 - Jan Mayen Fracture Zones
- 4 - Wyville Thomson/Ymir Ridge Thrust Complex
- 3 - Kialineq, Søndre Aputitêq and Patulajivit area
- 2 - Sødalen Area
- 1 - Lewisian Gneiss Complex

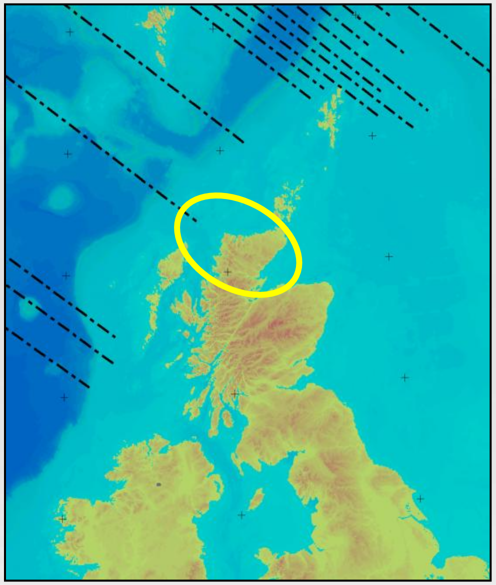


Bathymetric data clearly illustrate the presence of additional Fracture Zones, (not illustrated for sake of clarity).



UK Offshore/Onshore Linkage: Lewisian Gneiss Complex

- **Accreted as series of terranes in the Precambrian**
- **Accretion occurred before most brittle deformation**



- **Prominent NE-SW & NW-SE fault trends**
- **NW-SE faults produce the longest lineaments**
- **Originate in Archean (2490-2400 Ma): Steep NW-SE shear zones formed due to dextral transpression**
- **Reactivated during most subsequent tectonic episodes**

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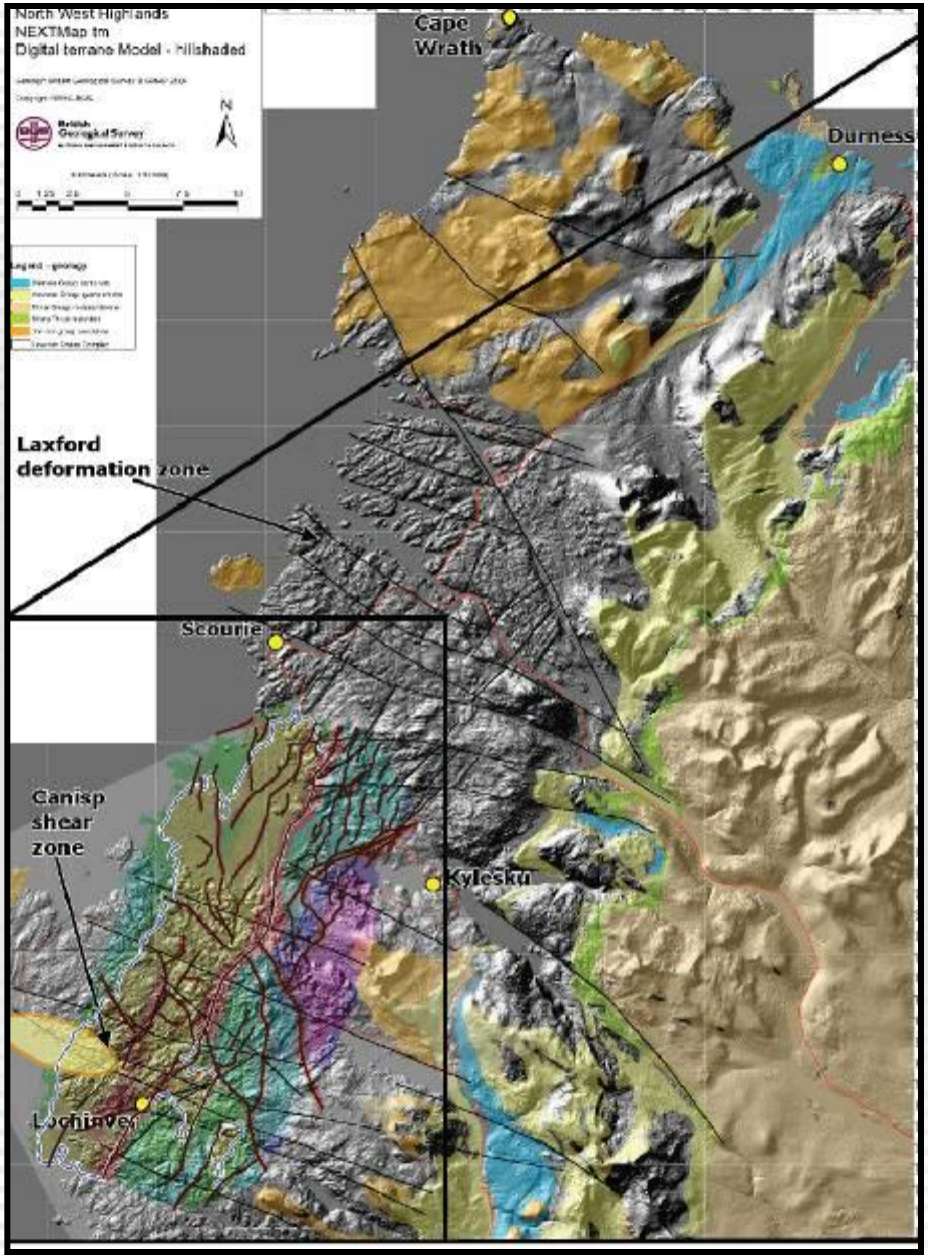
Pless, J. et al, 2010. Characterising fault networks in the Lewisian Gneiss Complex, NW Scotland: Implications for petroleum potential in the Clair Field basement, Faroe-Shetland Basin. AAPG, New Orleans – oral & poster presentation



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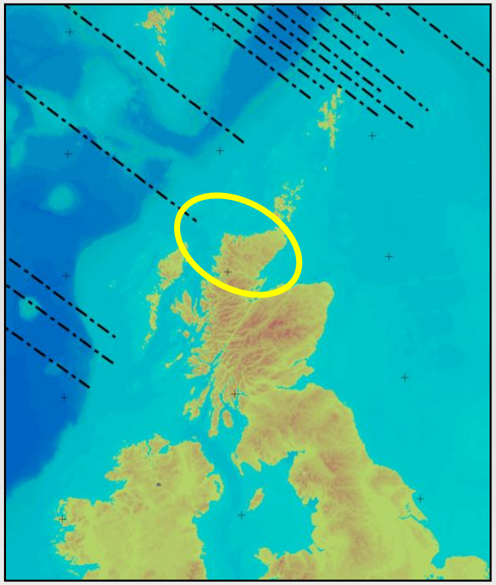

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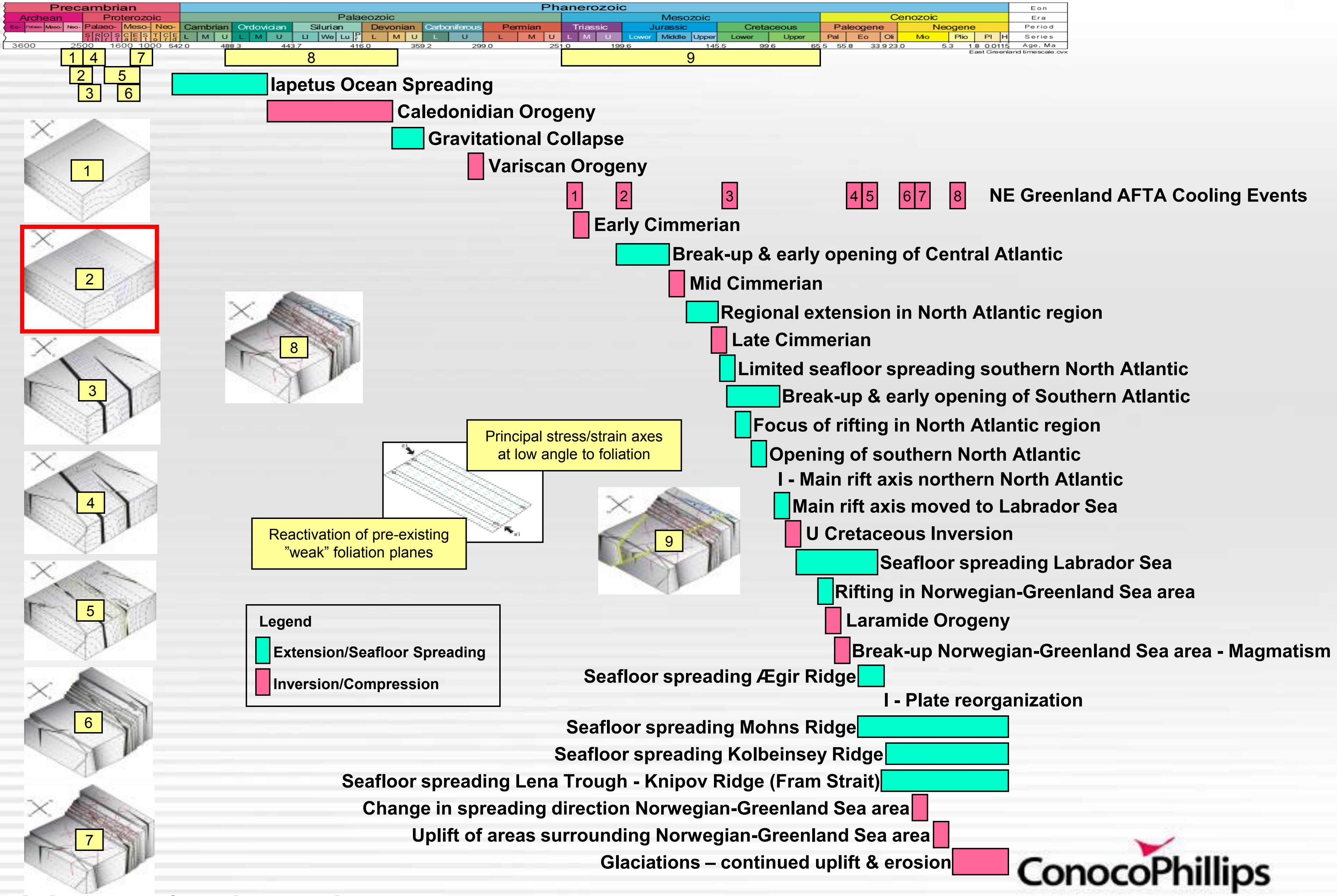
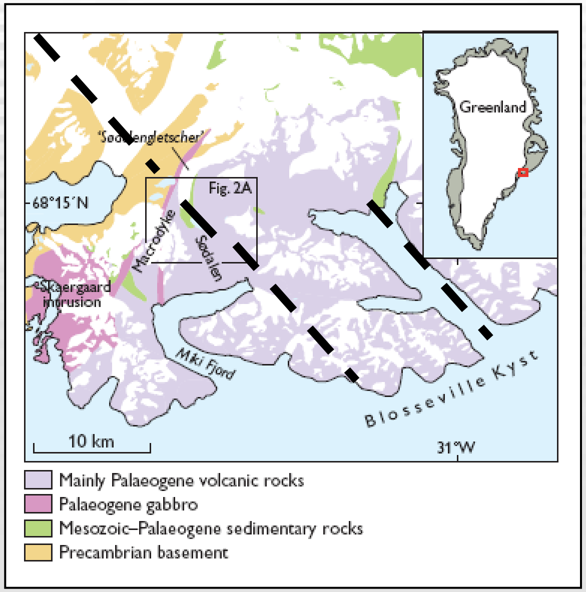
North Atlantic & Norwegian - Greenland Sea Deformation History

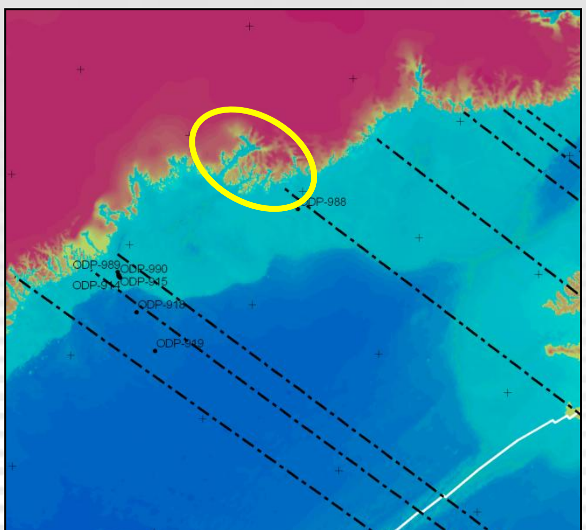


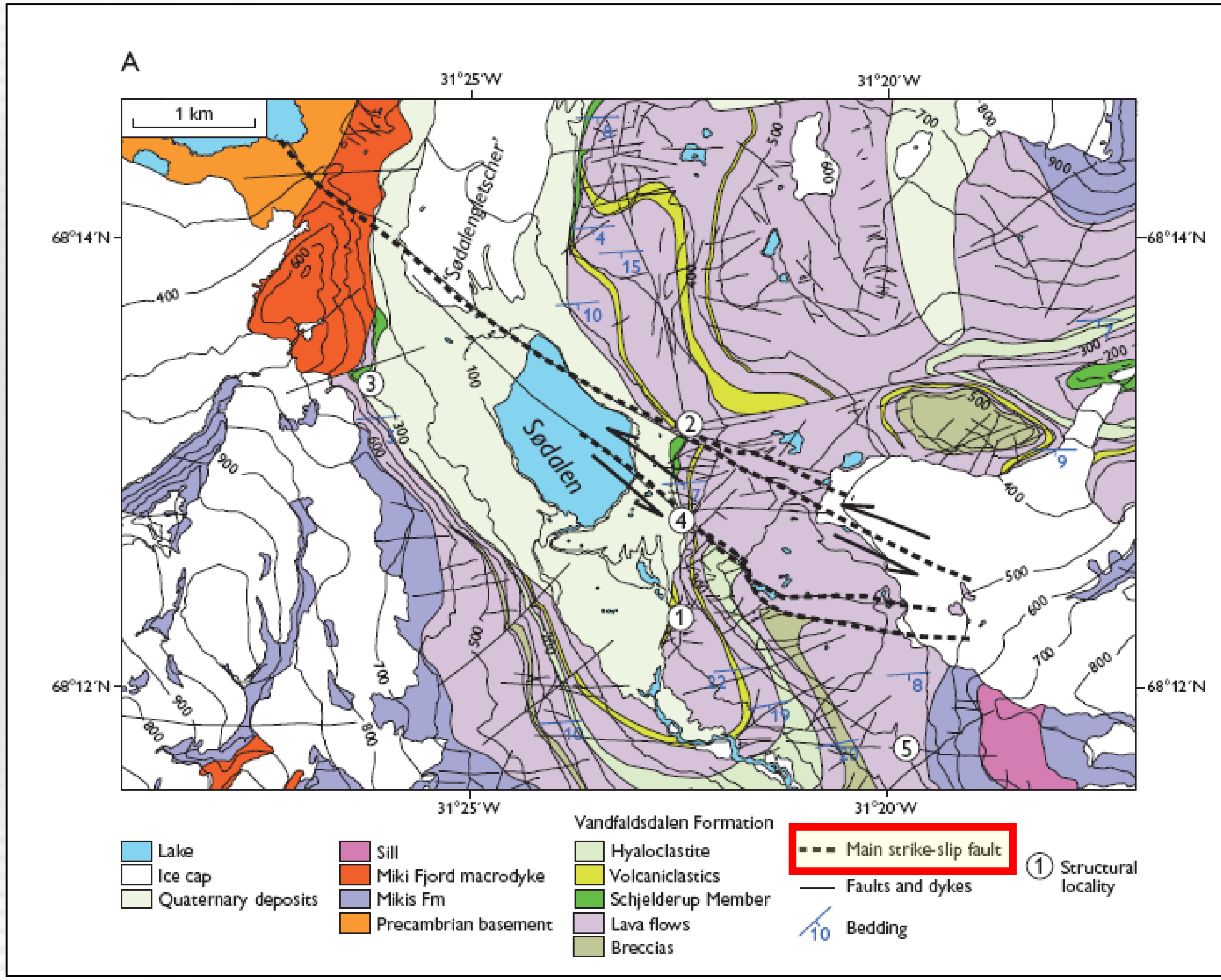
Block Diagrams from Pless, J. et al, 2010.

SE Greenland Offshore/Onshore Linkage: Sødalen Area

Simplified Geological Map







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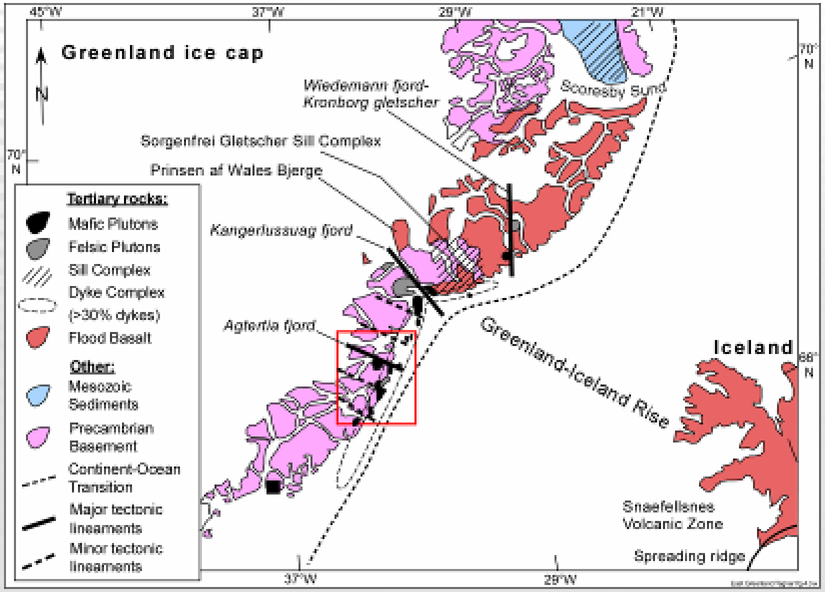
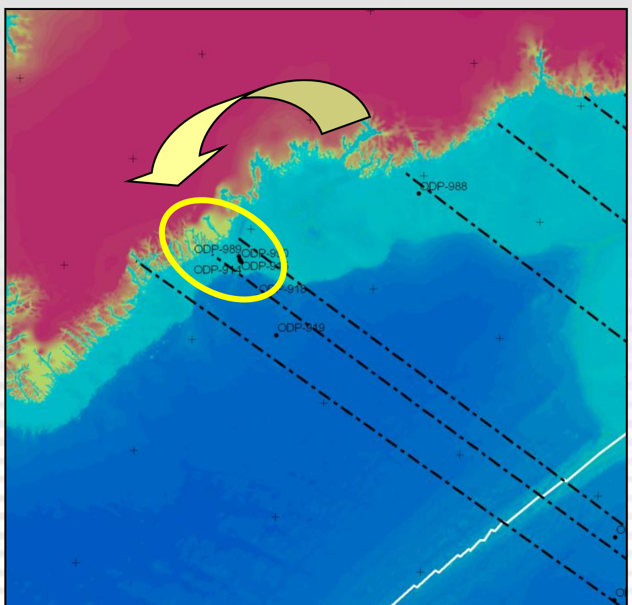
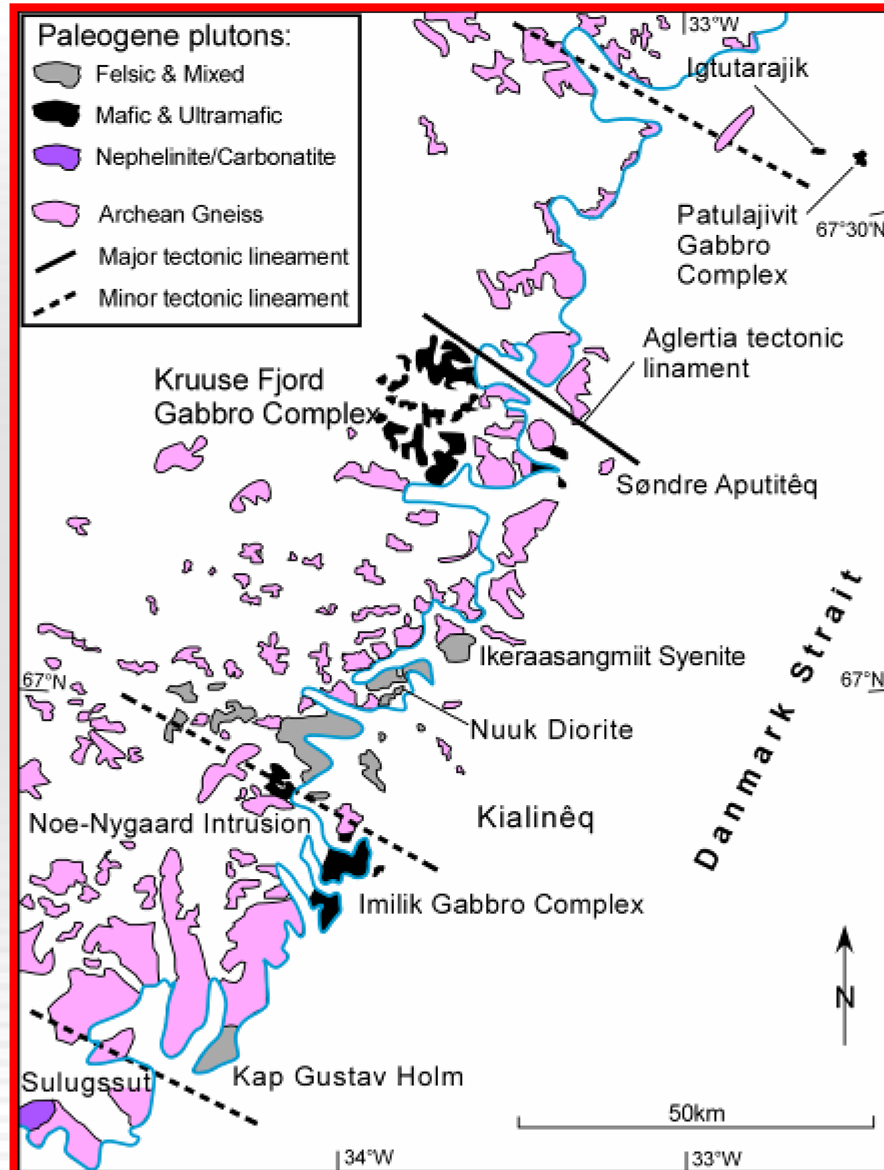
Guarnieri, P., 2011, Analysis of Palaeogene strike-slip tectonics along the southern East Greenland margin (Sødalen area). Bull. Geol. Soc. Den., 23, pp. 65-68. Reproduced with permission of GEUS

SE Greenland Offshore/Onshore Linkage: Kialineq, Søndre Aputitêq & Patulajivit area







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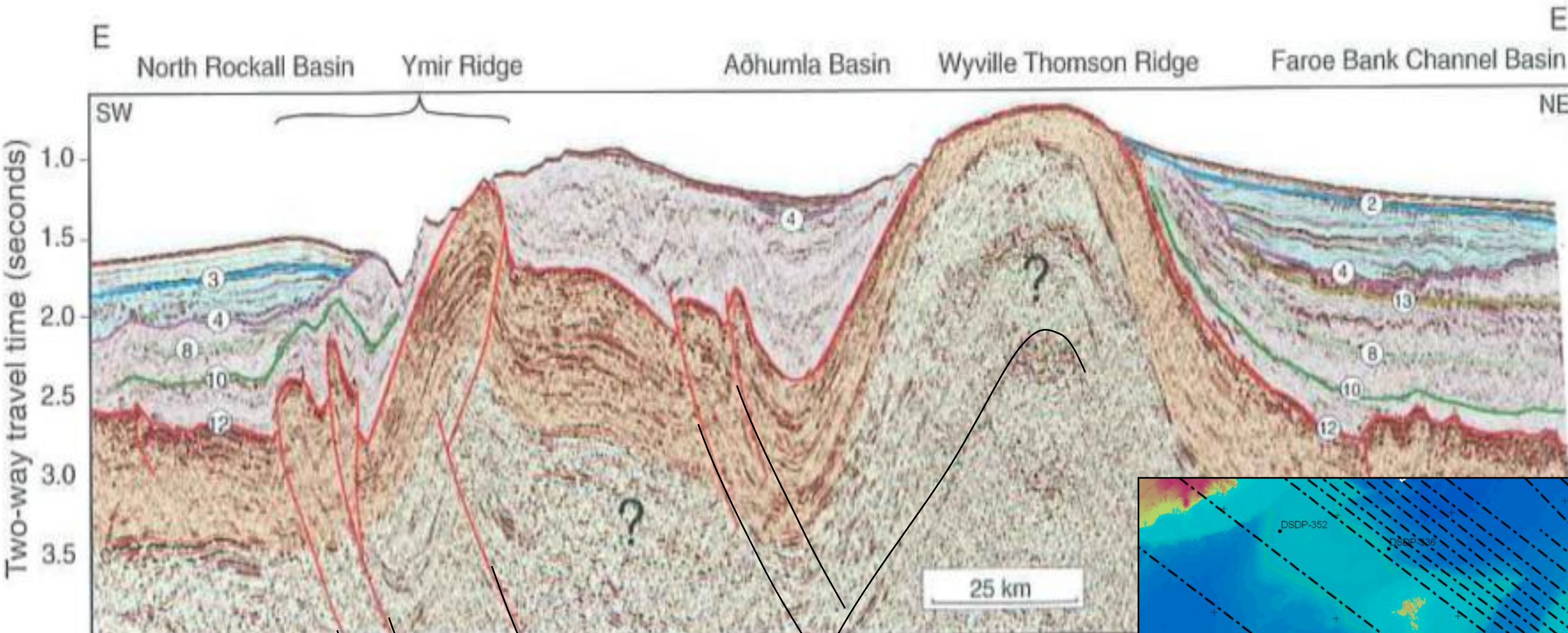
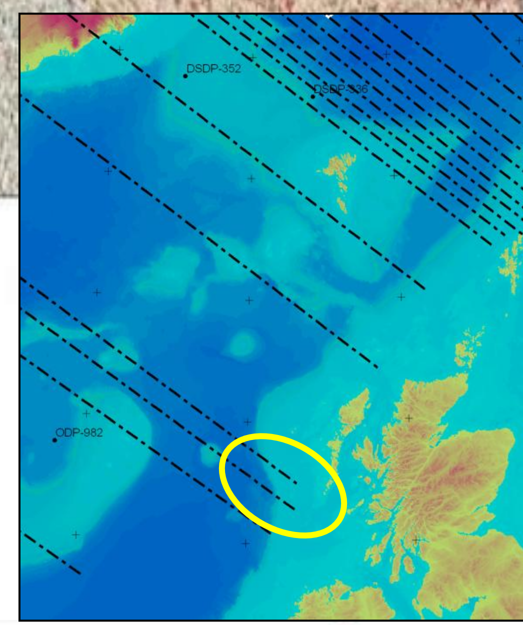
Redrawn and simplified after: Tegner, C. et al, 2008, 40Ar-39Ar ages of intrusions in East Greenland: Rift-to-drift transition over the Iceland hotspot. Lithos, pp. 480-500

UK Offshore/Onshore Linkage: Wyville Thomson/Ymir Ridge Thrust Complex





- **Two plates moving at low convergent angle causes space problem (plate reorientation due to opening of Fram Strait?)**
- **Easiest direction for relief is upwards.**
- **Wrench fault flower structures are not necessarily symmetrical.**
- **Faults coalesce and anastomose with depth.**

Figure 8, Ritchie, J. D. et al., 2008, The effects of Cenozoic compression within the Faroe-Shetland Basin. From: Johnson, H., Doré, A.G., Gatcliff, R.W., Holdsworth, R., Lundin, E.R. & Ritchie, J.D. (eds) The Nature and Origin of Compression in Passive Margins. Geological Society, London, Special Publications, 306, 121 – 136. Reproduced with permission of the Geological Society of London.

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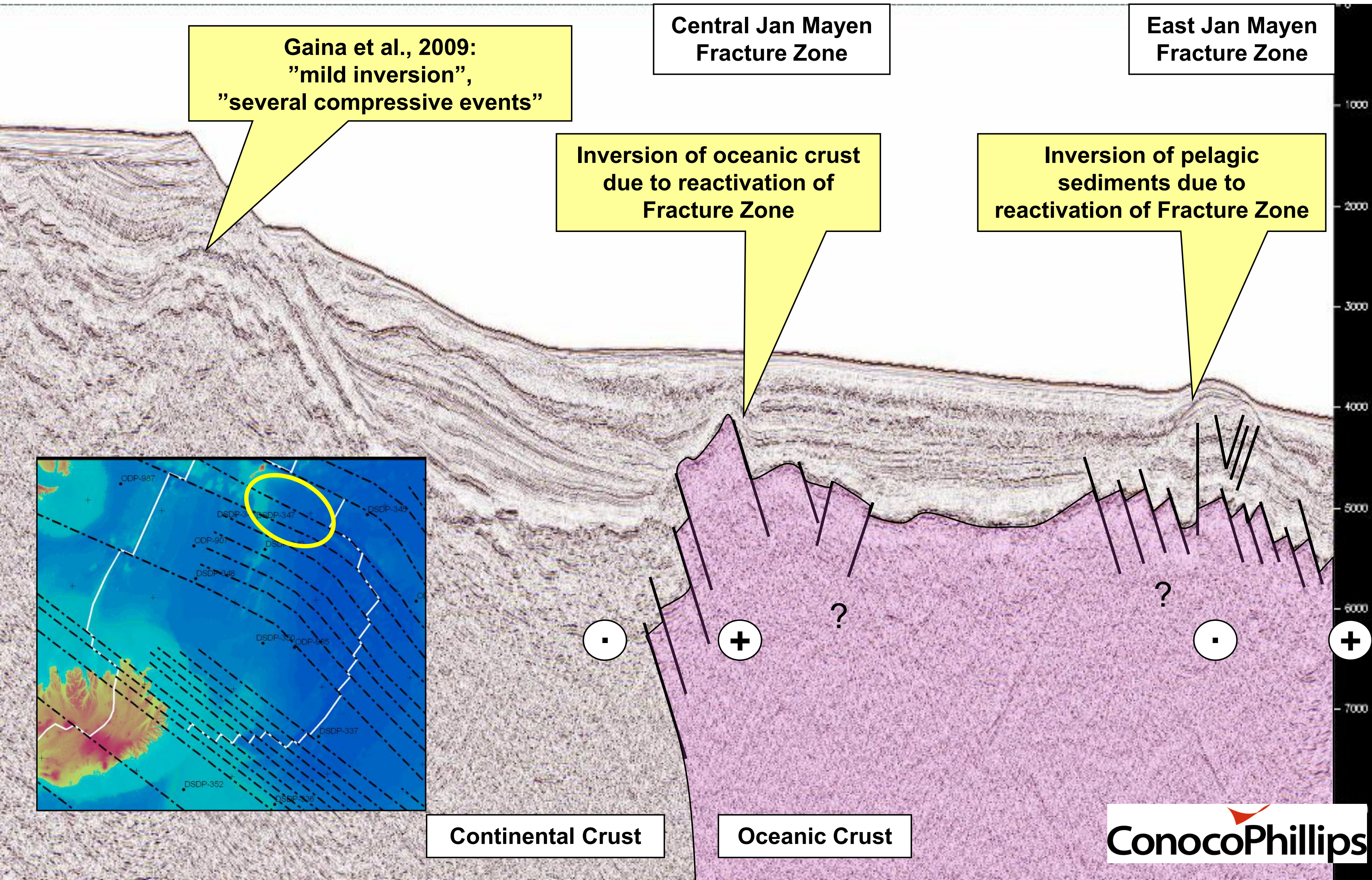
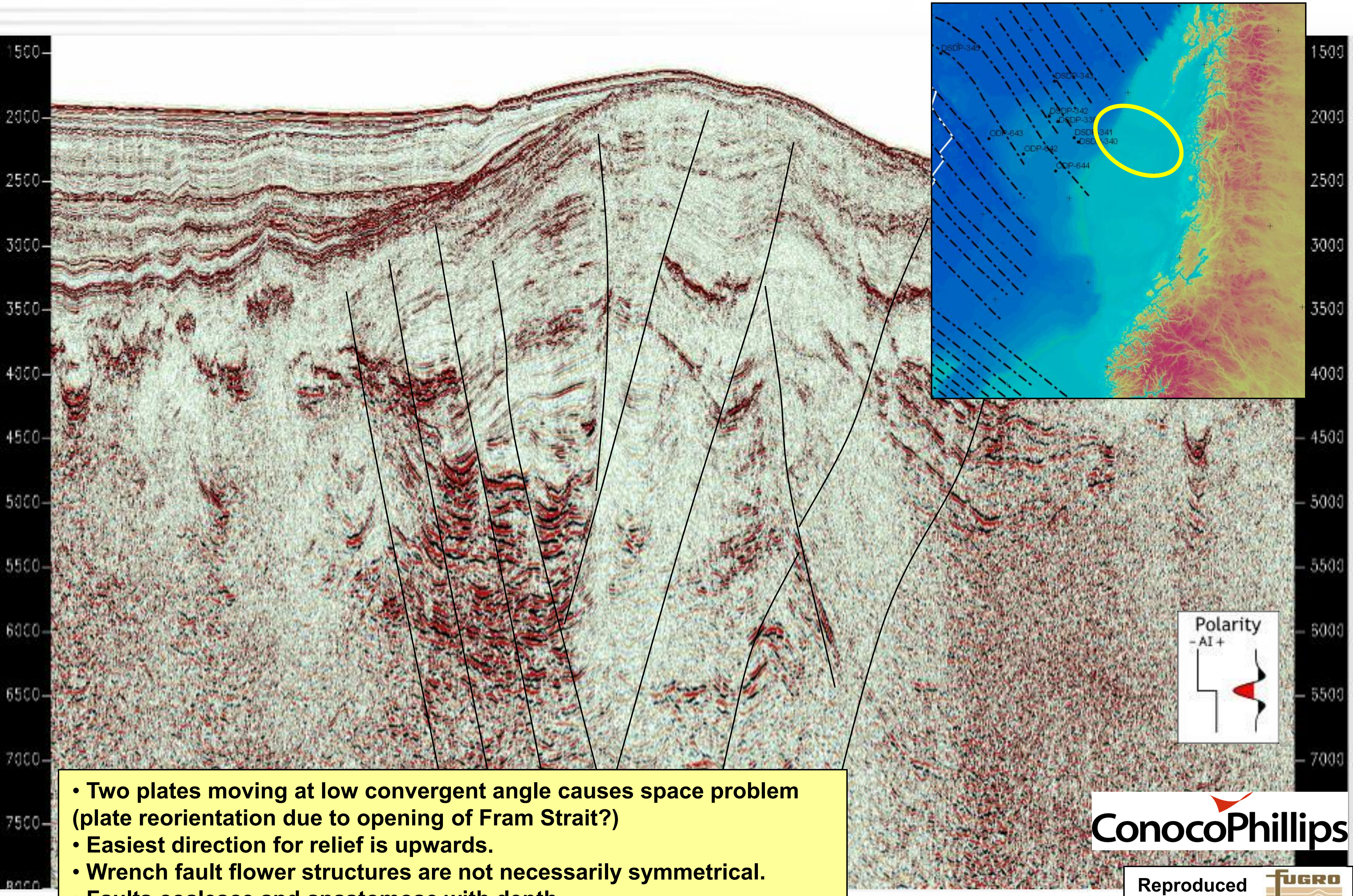
Central and East Jan Mayen Fracture Zones



Gaina, C. et al, 2009, Palaeocene–Recent plate boundaries in the NE Atlantic and the formation of the Jan Mayen microcontinent. J. Geol. Soc., 601–616.

Flower Structure – Naglfar Dome, Vøring Basin



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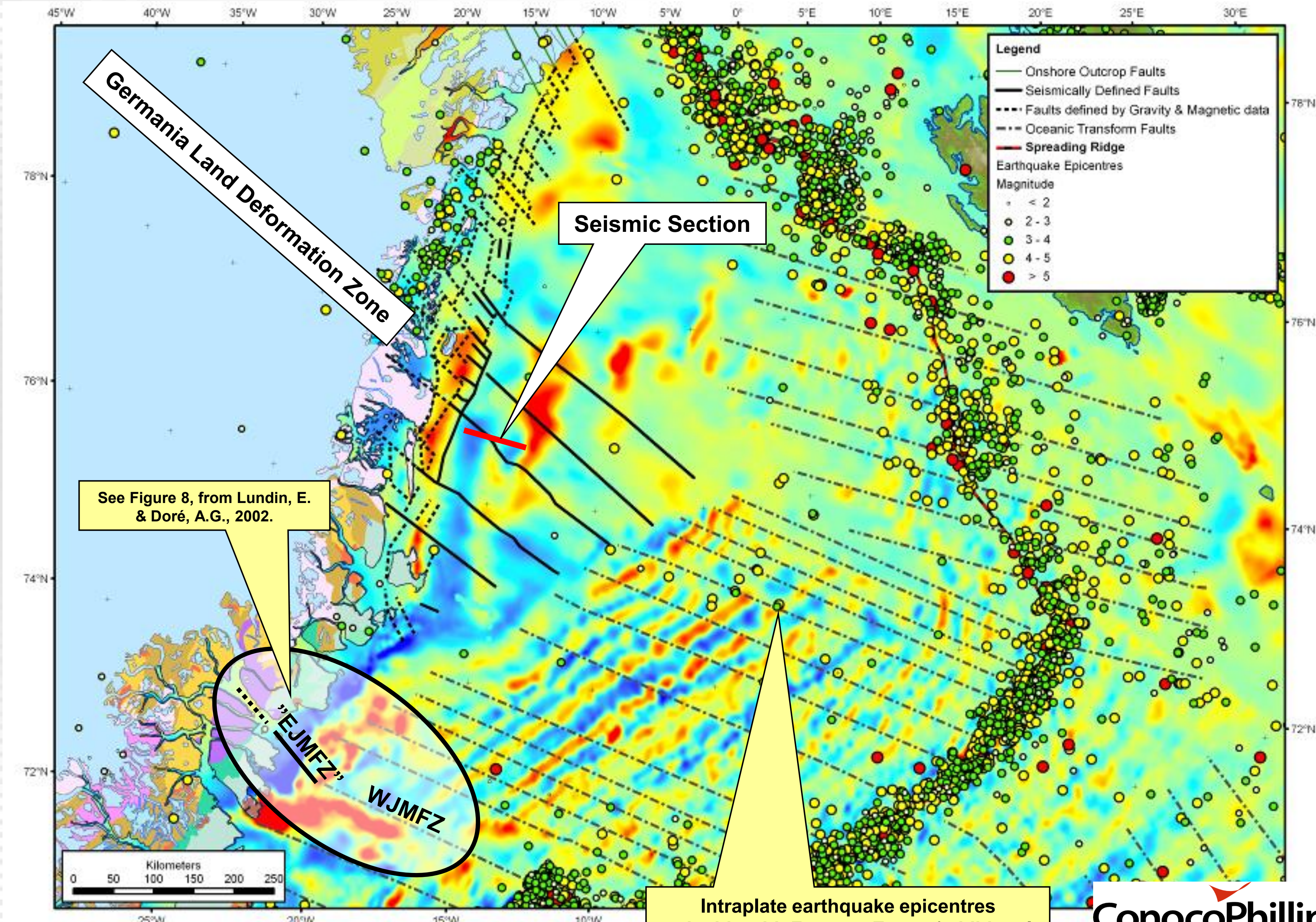
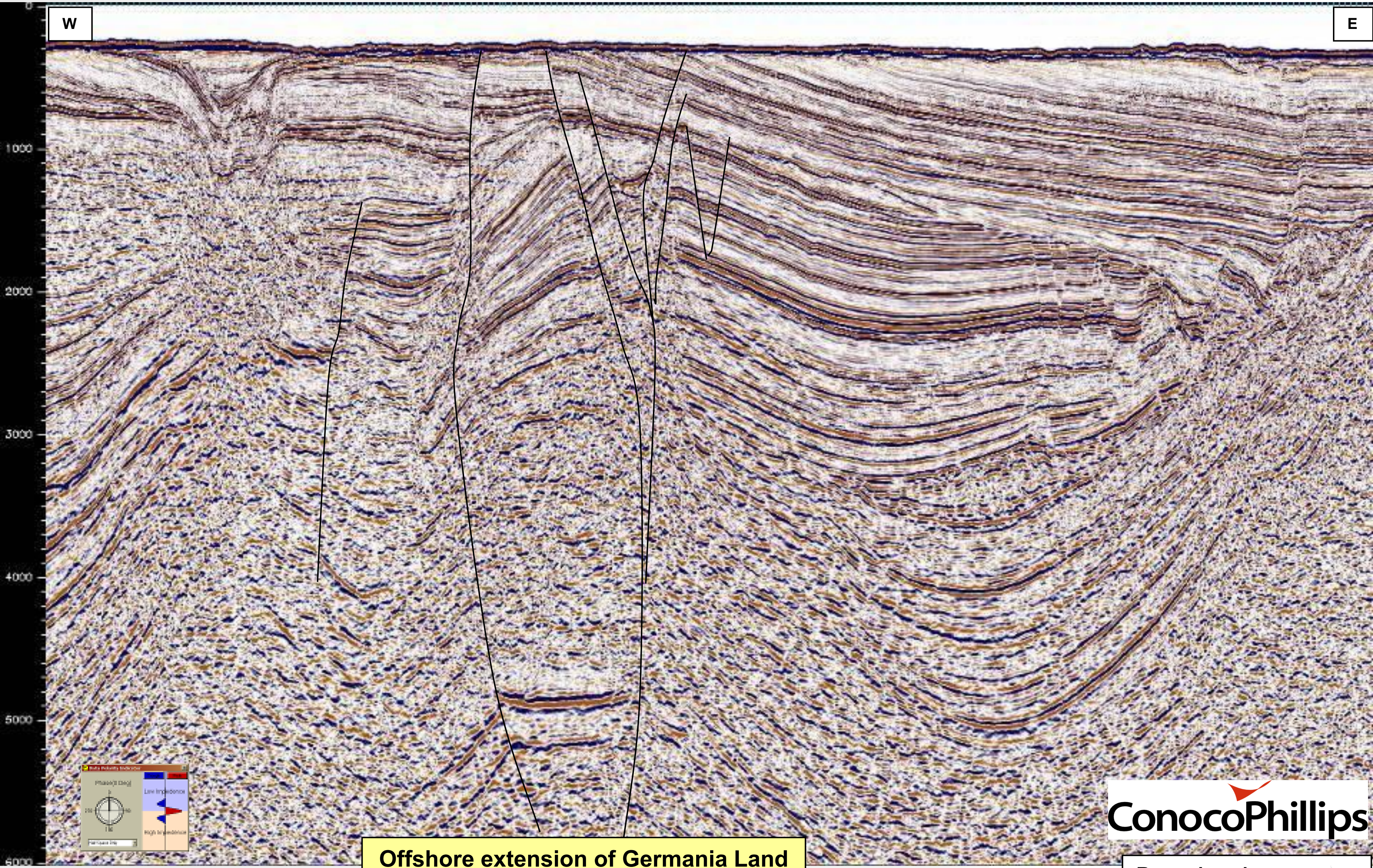
North East Greenland



Lundin, E. & Doré, A.G., 2002. Mid-Cenozoic post-breakup deformation in the "passive" margins bordering the Norwegian-Greenland Sea. Mar. Pet. Geol., 79-93

NE Greenland: NW-SE-trending Wrench Faulting

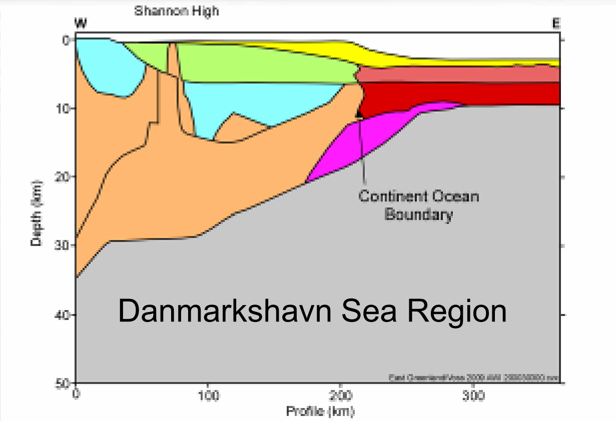


Offshore extension of Germania Land Deformation Zone

Norwegian - Greenland Sea: Asymmetric Conjugate Margins (2009)

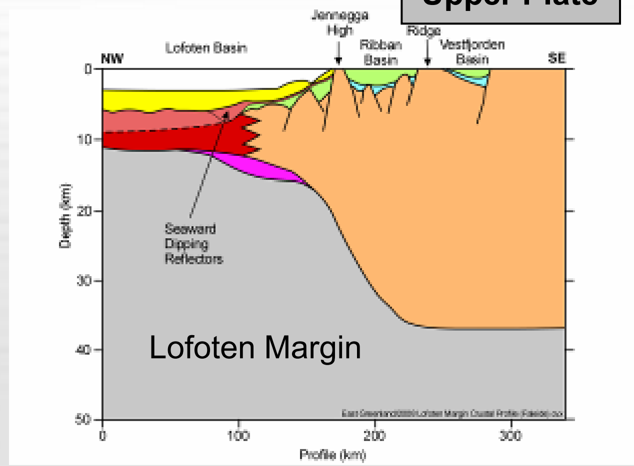
(Ocean Bottom Refraction Seismic Data)

Lower Plate



Simplified and redrawn from: Voss, M. et al, 2009, Variations in magmatic processes along the East Greenland volcanic margin. Geophys. J. Int., 755-782

Upper Plate



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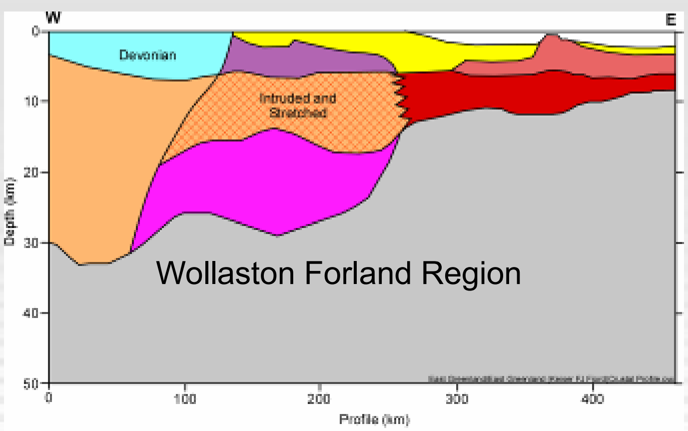

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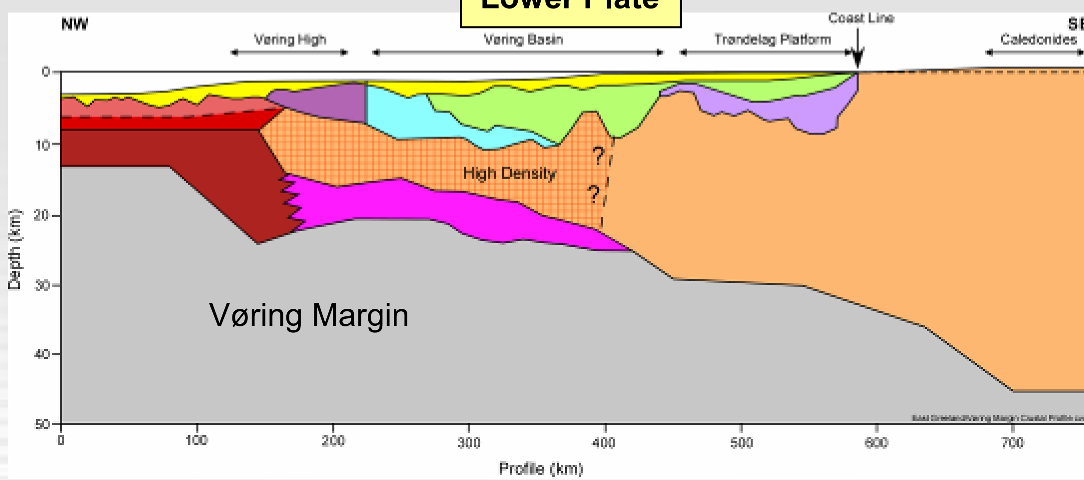
Lower Plate



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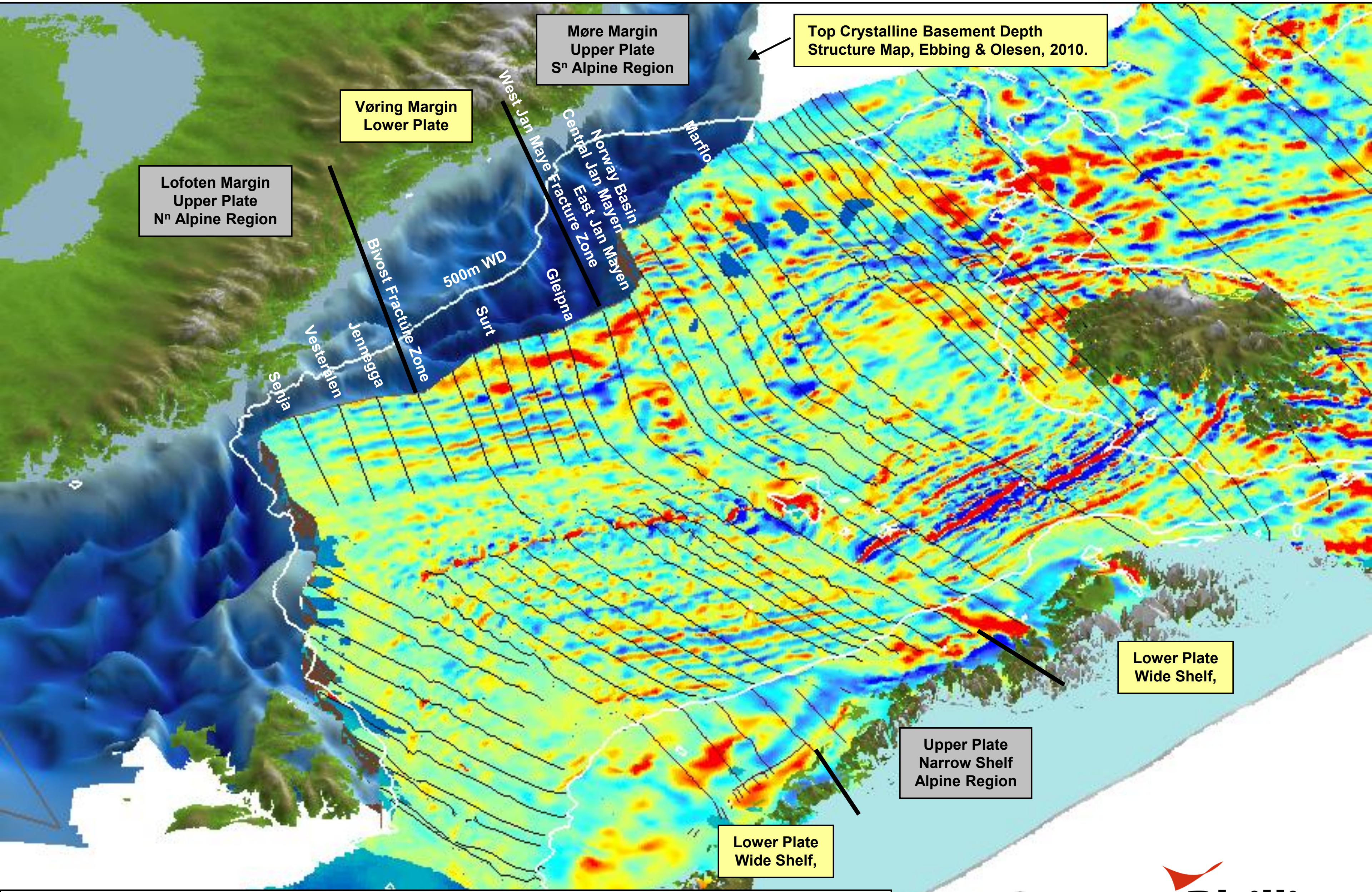
Norwegian - Greenland Sea: Asymmetric Conjugate Margins



Ebbing, J. & Olesen, O., 2010, New compilation of top basement and basement thickness for the Norwegian continental shelf reveals the segmentation of the passive margin system. From: Vining, B. A. & Pickering, S. C. (eds) Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference, 1–13.

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CONCLUSIONS

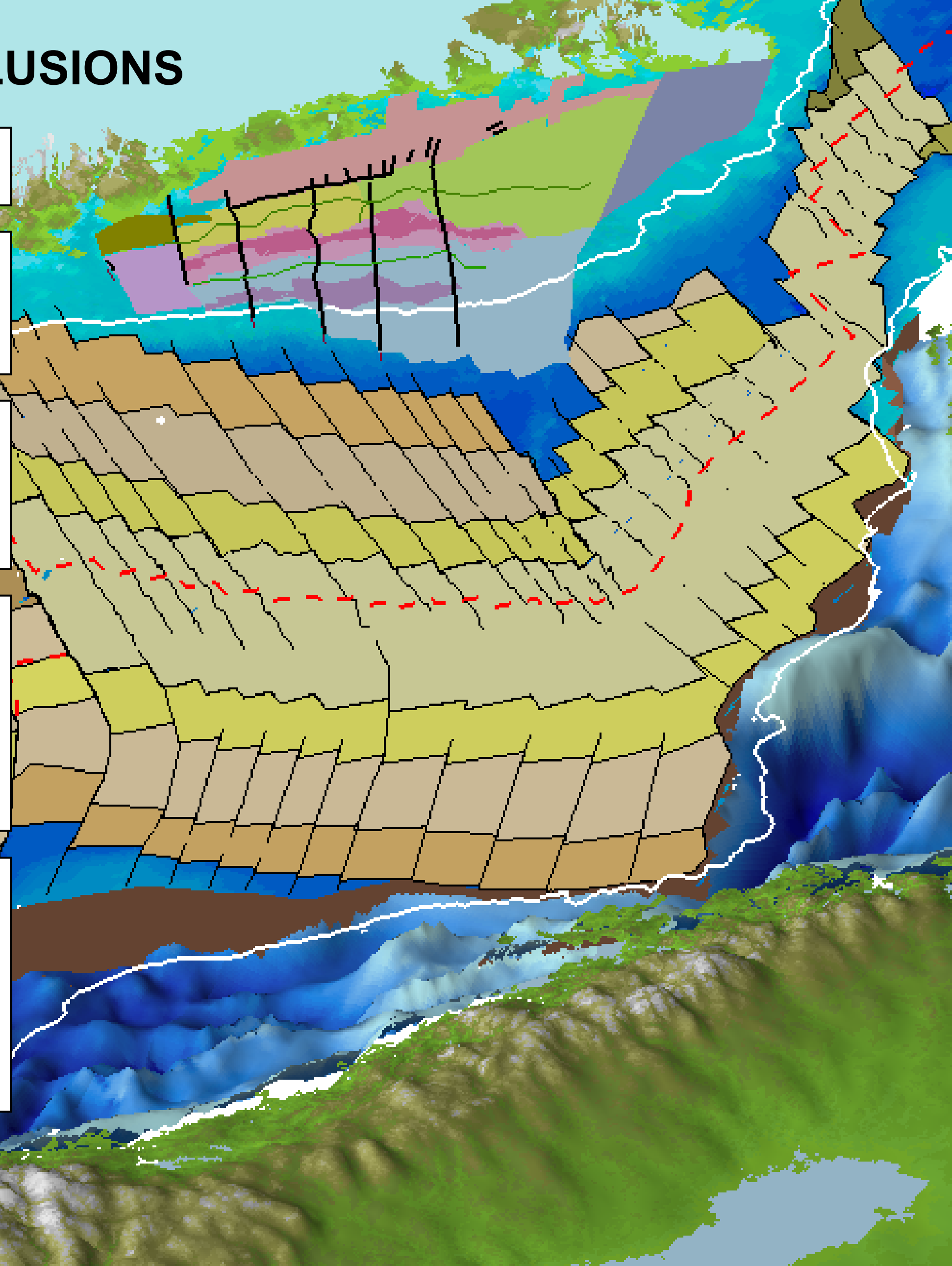
A simple symmetric spreading model can be used to explain the opening of the Norwegian – Greenland Sea.

NW-SE trending, coast-perpendicular fracture zones are recognized regionally in the deepwater and adjacent shelf, probably linked to onshore Precambrian basement fabric.

Transtensional, transpressional and inversion structuring associated with reactivation of the Mid-Ocean Ridge transform boundaries/fracture zones is obvious throughout the North Atlantic and Norwegian – Greenland Sea (as seen to the south of the Equator) .

- FZ Offshore/Onshore linked shear zones control:
  - Sediment entry points,
  - Provide hydrocarbon migration routes,
  - Create trapping geometries,

  &
  - Allow development of new exploration models.



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  - ConocoPhillips management for support for the publication of this article,
  - Jennifer Pless and Professor Bob Holdsworth, Durham University (Lewisian Outcrop Project),
  - Clair Field partnership (permission to share the Lewisian Outcrop Project ongoing research).

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